

## CLAIMS

- 1 1. A storage medium that contains instructions executable by a computer system to  
2 configure the computer system as a garbage collector that reclaims for reuse memory al-  
3 located by a mutator executing on the computer system, wherein the garbage collector  
4 performs a plurality of successive marking cycles, in each of which the garbage collector:
  - 5 A) performs a marking operation in which the garbage collector traces refer-  
6 ence chains from a root set and makes marks associated with respective  
7 objects thereby encountered;
  - 8 B) thereafter performs a succession of collection space increments within the  
9 marking cycle;
  - 10 C) repeatedly calculates a measure of the cumulative efficiency of collection  
11 that has taken place during the marking cycle and determines whether the  
12 cumulative efficiency thereby calculated satisfies a set of at least one  
13 marking-initiation criterion; and
  - 14 D) if so, terminates that marking cycle and begins the next marking cycle.
- 1 2. A storage medium as defined in claim 1 wherein one said marking-initiation crite-  
2 rion is that the cumulative efficiency has peaked.
- 1 3. A storage medium as defined in claim 2 wherein one said marking-initiation crite-  
2 rion is that at least a threshold number of collections have occurred during the marking  
3 cycle.
- 1 4. A storage medium as defined in claim 1 wherein the cumulative collection effi-  
2 ciency for a marking cycle is calculated as the ratio of an amount of memory reclaimed  
3 during that marking cycle to an amount of time taken to by collection during that marking  
4 cycle.

1       5. A storage medium as defined in claim 4 wherein, in determining the amount of  
2 memory reclaimed in a cycle, the garbage collector includes the memory reclaimed by all  
3 space-incremental-collection operations that take place after the end of that marking op-  
4 eration.

1       6. A storage medium as defined in claim 5 wherein:  
2           A) the garbage collector treats the heap as divided into regions; and  
3           B) the marking operation includes reclaiming regions in which all objects sat-  
4 isfy an unreachability criterion based on that marking operation's results.

1       7. A storage medium as defined in claim 6 wherein, in determining the amount of  
2 memory reclaimed in a cycle, the garbage collector includes the amount of memory re-  
3 claimed as part of the marking cycle's marking operation but omits any memory re-  
4 claimed by any space-incremental-collection operations that take place before the end of  
5 that marking operation.

1       8. A storage medium as defined in claim 4 wherein one said marking-initiation crite-  
2 rion is that the cumulative efficiency has peaked.

1       9. A storage medium as defined in claim 1 wherein:  
2           A) each of a plurality of the collection space increments reclaims a collection  
3              set within the heap; and  
4           B) the garbage collector bases the collection set's selection on the marks  
5              made by one said marking operation's results.

1       10. A storage medium as defined in claim 9 wherein:  
2           A) the garbage collector treats the heap as divided into regions, for which it  
3              maintains respective remembered sets that in the collection space incre-  
4              ments it uses to determine whether objects in the collection set are referred

5 to from outside the collection set and are therefore potentially reachable;  
6 and

7 B) the garbage collector additionally bases the collection set's selection on  
8 the sizes of the remembered sets.

1 11. A storage medium as defined in claim 9 wherein one said marking-initiation crite-  
2 rion is that the cumulative efficiency has peaked.

1 12. A storage medium as defined in claim 11 wherein the marking operation occurs at  
2 least in part concurrently with the mutator's execution.

1 13. A storage medium as defined in claim 12 wherein in each of a plurality of the col-  
2 lection space increments the garbage collector determines whether objects in an associ-  
3 ated collection set within the heap satisfy an unreachability criterion based on the mark-  
4 ing operation's results, evacuates potentially reachable objects from the collection set  
5 without evacuating any object thus identified, and reclaims the collection set.

1 14. A storage medium as defined in claim 9 wherein the marking operation occurs at  
2 least in part concurrently with the mutator's execution.

1 15. A storage medium as defined in claim 14 wherein in each of a plurality of the col-  
2 lection space increments the garbage collector determines whether objects in an associ-  
3 ated collection set within the heap satisfy an unreachability criterion based on the mark-  
4 ing operation's results, evacuates potentially reachable objects from the collection set  
5 without evacuating any object thus identified, and reclaims the collection set.

1 16. A storage medium as defined in claim 14 wherein one said marking-initiation cri-  
2 terion is that the cumulative efficiency has peaked.

- 1    17. A storage medium as defined in claim 9 wherein in each of a plurality of the collection space increments the garbage collector determines whether objects in an associated collection set within the heap satisfy an unreachability criterion based on the marking operation's results, evacuates potentially reachable objects from the collection set without evacuating any object thus identified, and reclaims the collection set.
- 1    18. A storage medium as defined in claim 17 wherein one said marking-initiation criterion is that the cumulative efficiency has peaked.
- 1    19. A storage medium as defined in claim 1 wherein the marking operation occurs at least in part concurrently with the mutator's execution.
- 1    20. A storage medium as defined in claim 19 wherein one said marking-initiation criterion is that the cumulative efficiency has peaked.
- 1    21. A storage medium as defined in claim 19 wherein in each of a plurality of the collection space increments the garbage collector determines whether objects in an associated collection set within the heap satisfy an unreachability criterion based on the marking operation's results, evacuates potentially reachable objects from the collection set without evacuating any object thus identified, and reclaims the collection set.
- 1    22. A storage medium as defined in claim 1 wherein in each of a plurality of the collection space increments the garbage collector determines whether objects in an associated collection set within the heap satisfy an unreachability criterion based on the marking operation's results, evacuates potentially reachable objects from the collection set without evacuating any object thus identified, and reclaims the collection set.
- 1    23. A storage medium as defined in claim 22 wherein one said marking-initiation criterion is that the cumulative efficiency has peaked.

- 1    24. For reclaiming for reuse memory allocated by a mutator executing on the com-  
2    puter system, a method comprising employing the computer system to performs a plural-  
3    ity of successive marking cycles, each of which includes:  
4       A) performing a marking operation by tracing reference chains from a root set  
5           and making marks associated with respective objects thereby encountered;  
6       B) thereafter performing a succession of collection space increments within  
7           the marking cycle;  
8       C) repeatedly calculating a measure of the cumulative efficiency of collection  
9           that has taken place during the marking cycle and determining whether the  
10          cumulative efficiency thereby calculated satisfies a set of at least one  
11          marking-initiation criterion; and  
12       D) if so, terminating that marking cycle and beginning the next marking cy-  
13           cle.

1    25. A method as defined in claim 24 wherein one said marking-initiation criterion is  
2    that the cumulative efficiency has peaked.

1    26. A method as defined in claim 25 wherein one said marking-initiation criterion is  
2    that at least a threshold number of collections have occurred during the marking cycle.

1    27. A method as defined in claim 24 wherein the cumulative collection efficiency for  
2    a marking cycle is calculated as the ratio of an amount of memory reclaimed during that  
3    marking cycle to an amount of time taken to by collection during that marking cycle.

1    28. A method as defined in claim 27 wherein, the memory reclaimed by all space-  
2    incremental-collection operations that take place after the end of that marking operation  
3    is included in determining the amount of memory reclaimed in a cycle.

1    29. A method as defined in claim 28 wherein:

- 2       A) the method includes treating the heap as divided into regions; and

- 3           B)    the marking operation includes reclaiming regions in which all objects sat-  
4           isfy an unreachability criterion based on that marking operation's results.
- 1   30.    A method as defined in claim 29 wherein, the amount of memory reclaimed as  
2   part of the marking cycle's marking operation is included in determining the amount of  
3   memory reclaimed in a cycle, but the amount of memory reclaimed by any space-  
4   incremental-collection operations that take place before the end of that marking operation  
5   is not.
- 1   31.    A method as defined in claim 27 wherein one said marking-initiation criterion is  
2   that the cumulative efficiency has peaked.
- 1   32.    A method as defined in claim 24 wherein:  
2        A)    each of a plurality of the collection space increments reclaims a collection  
3           set within the heap; and  
4        B)    the collection set's selection is based on the marks made by one said  
5           marking operation's results.
- 1   33.    A method as defined in claim 32 wherein the method includes:  
2        A)    treating the heap as divided into regions and maintaining therefor respec-  
3           tive remembered sets that in the collection space increments are used to  
4           determine whether objects in the collection set are referred to from outside  
5           the collection set and are therefore potentially reachable; and  
6        B)    additionally basing the collection set's selection on the sizes of the re-  
7           membered sets.
- 1   34.    A method as defined in claim 32 wherein one said marking-initiation criterion is  
2   that the cumulative efficiency has peaked.

- 1    35.    A method as defined in claim 34 wherein the marking operation occurs at least in  
2    part concurrently with the mutator's execution.
  
- 1    36.    A method as defined in claim 35 wherein each of a plurality of the collection  
2    space increments includes determining whether objects in an associated collection set  
3    within the heap satisfy an unreachability criterion based on the marking operation's re-  
4    sults, evacuating potentially reachable objects from the collection set without evacuating  
5    any object thus identified, and reclaiming the collection set.
  
- 1    37.    A method as defined in claim 32 wherein the marking operation occurs at least in  
2    part concurrently with the mutator's execution.
  
- 1    38.    A method as defined in claim 37 wherein each of a plurality of the collection  
2    space increments includes determining whether objects in an associated collection set  
3    within the heap satisfy an unreachability criterion based on the marking operation's re-  
4    sults, evacuating potentially reachable objects from the collection set without evacuating  
5    any object thus identified, and reclaiming the collection set.
  
- 1    39.    A method as defined in claim 37 wherein one said marking-initiation criterion is  
2    that the cumulative efficiency has peaked.
  
- 1    40.    A method as defined in claim 32 wherein each of a plurality of the collection  
2    space increments includes determining whether objects in an associated collection set  
3    within the heap satisfy an unreachability criterion based on the marking operation's re-  
4    sults, evacuating potentially reachable objects from the collection set without evacuating  
5    any object thus identified, and reclaiming the collection set.
  
- 1    41.    A method as defined in claim 40 wherein one said marking-initiation criterion is  
2    that the cumulative efficiency has peaked.

- 1    42. A method as defined in claim 24 wherein the marking operation occurs at least in  
2    part concurrently with the mutator's execution.
  
- 1    43. A method as defined in claim 42 wherein one said marking-initiation criterion is  
2    that the cumulative efficiency has peaked.
  
- 1    44. A method as defined in claim 42 wherein each of a plurality of the collection  
2    space increments includes determining whether objects in an associated collection set  
3    within the heap satisfy an unreachability criterion based on the marking operation's re-  
4    sults, evacuating potentially reachable objects from the collection set without evacuating  
5    any object thus identified, and reclaiming the collection set.
  
- 1    45. A method as defined in claim 24 wherein each of a plurality of the collection  
2    space increments includes determining whether objects in an associated collection set  
3    within the heap satisfy an unreachability criterion based on the marking operation's re-  
4    sults, evacuating potentially reachable objects from the collection set without evacuating  
5    any object thus identified, and reclaiming the collection set.
  
- 1    46. A method as defined in claim 45 wherein one said marking-initiation criterion is  
2    that the cumulative efficiency has peaked.
  
- 1    47. A computer system configured by stored instructions as a garbage collector that  
2    reclaims for reuse memory allocated by a mutator executing on the computer system,  
3    wherein the garbage collector performs a plurality of successive marking cycles, in each  
4    of which the garbage collector:
  - 5        A) performs a marking operation in which the garbage collector traces refer-  
6        ence chains from a root set and makes marks associated with respective  
7        objects thereby encountered;
  - 8        B) thereafter performs a succession of collection space increments within the  
9        marking cycle;

- 10           C) repeatedly calculates a measure of the cumulative efficiency of collection  
11           that has taken place during the marking cycle and determines whether the  
12           cumulative efficiency thereby calculated satisfies a set of at least one  
13           marking-initiation criterion; and  
14           D) if so, terminates that marking cycle and begins the next marking cycle.

1       48. A computer system as defined in claim 47 wherein one said marking-initiation  
2       criterion is that the cumulative efficiency has peaked.

1       49. A computer system as defined in claim 48 wherein one said marking-initiation  
2       criterion is that at least a threshold number of collections have occurred during the mark-  
3       ing cycle.

1       50. A computer system as defined in claim 47 wherein the cumulative collection effi-  
2       ciency for a marking cycle is calculated as the ratio of an amount of memory reclaimed  
3       during that marking cycle to an amount of time taken to by collection during that marking  
4       cycle.

1       51. A computer system as defined in claim 50 wherein, in determining the amount of  
2       memory reclaimed in a cycle, the garbage collector includes the memory reclaimed by all  
3       space-incremental-collection operations that take place after the end of that marking op-  
4       eration.

1       52. A computer system as defined in claim 51 wherein:  
2           A) the garbage collector treats the heap as divided into regions; and  
3           B) the marking operation includes reclaiming regions in which all objects sat-  
4           isfy an unreachability criterion based on that marking operation's results.

1       53. A computer system as defined in claim 52 wherein, in determining the amount of  
2       memory reclaimed in a cycle, the garbage collector includes the amount of memory re-

3 claimed as part of the marking cycle's marking operation but omits any memory re-  
4 claimed by any space-incremental-collection operations that take place before the end of  
5 that marking operation.

1 54. A computer system as defined in claim 50 wherein one said marking-initiation  
2 criterion is that the cumulative efficiency has peaked.

1 55. A computer system as defined in claim 47 wherein:  
2 A) each of a plurality of the collection space increments reclaims a collection  
3 set within the heap; and  
4 B) the garbage collector bases the collection set's selection on the marks  
5 made by one said marking operation's results.

1 56. A computer system as defined in claim 55 wherein:  
2 A) the garbage collector treats the heap as divided into regions, for which it  
3 maintains respective remembered sets that in the collection space incre-  
4 ments it uses to determine whether objects in the collection set are referred  
5 to from outside the collection set and are therefore potentially reachable;  
6 and  
7 B) the garbage collector additionally bases the collection set's selection on  
8 the sizes of the remembered sets.

1 57. A computer system as defined in claim 55 wherein one said marking-initiation  
2 criterion is that the cumulative efficiency has peaked.

1 58. A computer system as defined in claim 57 wherein the marking operation occurs  
2 at least in part concurrently with the mutator's execution.

1 59. A computer system as defined in claim 58 wherein in each of a plurality of the  
2 collection space increments the garbage collector determines whether objects in an asso-

3 ciated collection set within the heap satisfy an unreachability criterion based on the mark-  
4 ing operation's results, evacuates potentially reachable objects from the collection set  
5 without evacuating any object thus identified, and reclaims the collection set.

1 60. A computer system as defined in claim 55 wherein the marking operation occurs  
2 at least in part concurrently with the mutator's execution.

1 61. A computer system as defined in claim 60 wherein in each of a plurality of the  
2 collection space increments the garbage collector determines whether objects in an asso-  
3 ciated collection set within the heap satisfy an unreachability criterion based on the mark-  
4 ing operation's results, evacuates potentially reachable objects from the collection set  
5 without evacuating any object thus identified, and reclaims the collection set.

1 62. A computer system as defined in claim 60 wherein one said marking-initiation  
2 criterion is that the cumulative efficiency has peaked.

1 63. A computer system as defined in claim 55 wherein in each of a plurality of the  
2 collection space increments the garbage collector determines whether objects in an asso-  
3 ciated collection set within the heap satisfy an unreachability criterion based on the mark-  
4 ing operation's results, evacuates potentially reachable objects from the collection set  
5 without evacuating any object thus identified, and reclaims the collection set.

1 64. A computer system as defined in claim 63 wherein one said marking-initiation  
2 criterion is that the cumulative efficiency has peaked.

1 65. A computer system as defined in claim 47 wherein the marking operation occurs  
2 at least in part concurrently with the mutator's execution.

1 66. A computer system as defined in claim 65 wherein one said marking-initiation  
2 criterion is that the cumulative efficiency has peaked.

1       67. A computer system as defined in claim 65 wherein in each of a plurality of the  
2 collection space increments the garbage collector determines whether objects in an asso-  
3 ciated collection set within the heap satisfy an unreachability criterion based on the mark-  
4 ing operation's results, evacuates potentially reachable objects from the collection set  
5 without evacuating any object thus identified, and reclaims the collection set.

1       68. A computer system as defined in claim 47 wherein in each of a plurality of the  
2 collection space increments the garbage collector determines whether objects in an asso-  
3 ciated collection set within the heap satisfy an unreachability criterion based on the mark-  
4 ing operation's results, evacuates potentially reachable objects from the collection set  
5 without evacuating any object thus identified, and reclaims the collection set.

1       69. A computer system as defined in claim 68 wherein one said marking-initiation  
2 criterion is that the cumulative efficiency has peaked.

1       70. An electromagnetic signal that represents instructions executable by a computer  
2 system to configure the computer system as a garbage collector that reclaims for reuse  
3 memory allocated by a mutator executing on the computer system, wherein the garbage  
4 collector performs a plurality of successive marking cycles, in each of which the garbage  
5 collector:

- 6             A) performs a marking operation in which the garbage collector traces refer-  
7 ence chains from a root set and makes marks associated with respective  
8 objects thereby encountered;
- 9             B) thereafter performs a succession of collection space increments within the  
10 marking cycle;
- 11            C) repeatedly calculates a measure of the cumulative efficiency of collection  
12 that has taken place during the marking cycle and determines whether the  
13 cumulative efficiency thereby calculated satisfies a set of at least one  
14 marking-initiation criterion; and

15 D) if so, terminates that marking cycle and begins the next marking cycle.

1 71. An electromagnetic signal as defined in claim 70 wherein one said marking-  
2 initiation criterion is that the cumulative efficiency has peaked.

1 72. An electromagnetic signal as defined in claim 71 wherein one said marking-  
2 initiation criterion is that at least a threshold number of collections have occurred during  
3 the marking cycle.

1 73. An electromagnetic signal as defined in claim 70 wherein the cumulative collec-  
2 tion efficiency for a marking cycle is calculated as the ratio of an amount of memory re-  
3 claimed during that marking cycle to an amount of time taken to by collection during that  
4 marking cycle.

1 74. An electromagnetic signal as defined in claim 73 wherein, in determining the  
2 amount of memory reclaimed in a cycle, the garbage collector includes the memory re-  
3 claimed by all space-incremental-collection operations that take place after the end of that  
4 marking operation.

1 75. An electromagnetic signal as defined in claim 74 wherein:  
2 A) the garbage collector treats the heap as divided into regions; and  
3 B) the marking operation includes reclaiming regions in which all objects sat-  
4 isfy an unreachability criterion based on that marking operation's results.

1 76. An electromagnetic signal as defined in claim 75 wherein, in determining the  
2 amount of memory reclaimed in a cycle, the garbage collector includes the amount of  
3 memory reclaimed as part of the marking cycle's marking operation but omits any mem-  
4 ory reclaimed by any space-incremental-collection operations that take place before the  
5 end of that marking operation.

1    77. An electromagnetic signal as defined in claim 73 wherein one said marking-  
2    initiation criterion is that the cumulative efficiency has peaked.

1    78. An electromagnetic signal as defined in claim 70 wherein:  
2       A) each of a plurality of the collection space increments reclaims a collection  
3           set within the heap; and  
4       B) the garbage collector bases the collection set's selection on the marks  
5           made by one said marking operation's results.

1    79. An electromagnetic signal as defined in claim 78 wherein:  
2       A) the garbage collector treats the heap as divided into regions, for which it  
3           maintains respective remembered sets that in the collection space incre-  
4           ments it uses to determine whether objects in the collection set are referred  
5           to from outside the collection set and are therefore potentially reachable;  
6           and  
7       B) the garbage collector additionally bases the collection set's selection on  
8           the sizes of the remembered sets.

1    80. An electromagnetic signal as defined in claim 78 wherein one said marking-  
2    initiation criterion is that the cumulative efficiency has peaked.

1    81. An electromagnetic signal as defined in claim 80 wherein the marking operation  
2    occurs at least in part concurrently with the mutator's execution.

1    82. An electromagnetic signal as defined in claim 81 wherein in each of a plurality of  
2    the collection space increments the garbage collector determines whether objects in an  
3    associated collection set within the heap satisfy an unreachability criterion based on the  
4    marking operation's results, evacuates potentially reachable objects from the collection  
5    set without evacuating any object thus identified, and reclaims the collection set.

- 1    83. An electromagnetic signal as defined in claim 78 wherein the marking operation
- 2    occurs at least in part concurrently with the mutator's execution.
  
- 1    84. An electromagnetic signal as defined in claim 83 wherein in each of a plurality of the collection space increments the garbage collector determines whether objects in an associated collection set within the heap satisfy an unreachability criterion based on the marking operation's results, evacuates potentially reachable objects from the collection set without evacuating any object thus identified, and reclaims the collection set.
  
- 1    85. An electromagnetic signal as defined in claim 83 wherein one said marking-initiation criterion is that the cumulative efficiency has peaked.
  
- 1    86. An electromagnetic signal as defined in claim 78 wherein in each of a plurality of the collection space increments the garbage collector determines whether objects in an associated collection set within the heap satisfy an unreachability criterion based on the marking operation's results, evacuates potentially reachable objects from the collection set without evacuating any object thus identified, and reclaims the collection set.
  
- 1    87. An electromagnetic signal as defined in claim 86 wherein one said marking-initiation criterion is that the cumulative efficiency has peaked.
  
- 1    88. An electromagnetic signal as defined in claim 70 wherein the marking operation
- 2    occurs at least in part concurrently with the mutator's execution.
  
- 1    89. An electromagnetic signal as defined in claim 88 wherein one said marking-initiation criterion is that the cumulative efficiency has peaked.
  
- 1    90. An electromagnetic signal as defined in claim 88 wherein in each of a plurality of the collection space increments the garbage collector determines whether objects in an associated collection set within the heap satisfy an unreachability criterion based on the

4 marking operation's results, evacuates potentially reachable objects from the collection  
5 set without evacuating any object thus identified, and reclaims the collection set.

1 91. An electromagnetic signal as defined in claim 70 wherein in each of a plurality of  
2 the collection space increments the garbage collector determines whether objects in an  
3 associated collection set within the heap satisfy an unreachability criterion based on the  
4 marking operation's results, evacuates potentially reachable objects from the collection  
5 set without evacuating any object thus identified, and reclaims the collection set.

1 92. An electromagnetic signal as defined in claim 91 wherein one said marking-  
2 initiation criterion is that the cumulative efficiency has peaked.

1 93. A garbage collector for reclaiming for reuse memory allocated by a mutator exe-  
2 cuting on the computer system, the garbage collector including:

- 3 A) means for performing a marking operation by tracing reference chains  
4 from a root set and making marks associated with respective objects  
5 thereby encountered;
- 6 B) means for thereafter performing a succession of collection space incre-  
7 ments within the marking cycle;
- 8 C) means for repeatedly calculating a measure of the cumulative efficiency of  
9 collection that has taken place during a marking cycle that begins with the  
10 marking operation and determining whether the cumulative efficiency  
11 thereby calculated satisfies a set of at least one marking-initiation crite-  
12 rion; and
- 13 D) means for, if so, terminating that marking cycle and beginning a subse-  
14 quent marking cycle.